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Probing the incompressibility of nuclear matter at ultra-high density through the prompt collapse of asymmetric neutron star binaries

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Using 250 neutron star merger simulations with microphysics, we explore for the first time the role of nuclear incompressibility in the prompt collapse threshold for binaries with different mass ratios. We demonstrate that observations of prompt collapse thresholds, either from binaries with two different mass ratios or with one mass ratio but combined with the knowledge of the maximum neutron star mass or compactness, will constrain the incompressibility at the maximum neutron star density, K_{\max} to within tens of percent. This, otherwise inaccessible, measure of K_{\max} can potentially reveal the presence of hyperons or quarks inside neutron stars.

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Introduction.— The equation of state (EOS) of neutron star (NS) matter is one of the most fundamental, yet elusive, relations in physics [1, 2]. It lays at the interface between several disciplines including nuclear physics, high-energy astrophysics, heavy-ion collisions, multimessenger astronomy and gravitational wave (GW) physics. Our knowledge of NS matter properties is still partial, mostly due to the difficulties in studying strongly interacting bulk matter in the low energy limit typical of nuclear interactions [3]. Even the appropriate degrees of freedom are uncertain: while nucleons are the relevant species around the nuclear saturation density, $n_0 = 0.16 \text{ fm}^{-3}$, it is still unclear if hyperons [4, 5] or a phase transition to quark matter [6–8] can appear at densities $n \gtrsim 2n_0$ in NS interiors.

NS EOS models are experimentally constrained by the masses of ordinary nuclei, as well as by the energy per baryon and its derivatives with respect to baryon density, n_b , around n_0 and close to isospin symmetry, i.e. for symmetry parameter $\delta \equiv (n_n - n_p)/n_b \approx 0$, $n_{n,p}$ being the density of neutrons and protons. If P is the matter pressure, the nuclear incompressibility of cold nuclear matter at fixed composition is defined as

$$K(n_b, \delta) \equiv 9 \frac{\partial P}{\partial n_b} \Big|_{T=0, \delta=\text{const}}. \quad (1)$$

It describes the response of matter to compression and its value can be currently measured only for symmetric matter at saturation density, K_{sat} , although with some controversy [9–13]. While isoscalar giant monopole resonance experiments for closed shell nuclei provided $K_{\text{sat}} = (240 \pm 20) \text{ MeV}$, studies based on open-shell nuclei reported quite different values in the range 250 MeV–

315 MeV [12] or even values around 200 MeV [13]. Nevertheless, K_{sat} is unconstrained at densities and compositions relevant for NSs (far from $n \approx n_0$ and $\delta \approx 0$). In particular, the NS central density increases monotonically with the NS mass and at the stability limit, corresponding to mass and radius ($M_{\text{max}}^{\text{TOV}}$, $R_{\text{max}}^{\text{TOV}}$), can reach $n_{\text{max}}^{\text{TOV}} \sim 4 - 7n_0$, depending on the EOS. Moreover, for $n_b \gtrsim n_0$, β -equilibrated matter is very neutron rich, $\delta_{\text{eq}} \sim 1$.

In addition to nuclear constraints, astrophysical NS properties provide useful insights on the EOS. Constraints derived from the observation of massive, isolated NS [14–20], from GW signals [21, 22] and multimessenger observations of binary neutron star (BNS) mergers [23–28], or by their combination [29, 30], are very informative about the high density regime. A key phenomenon in this respect is the prompt collapse (PC) to black hole (BH) of the merger remnant, since this behavior can influence both the GW and electromagnetic (EM) signals produced by BNS mergers [31–36]. The PC behavior of equal mass BNSs was extensively explored in Ref. [37–43]. It was shown, for example, that the threshold mass for PC, M_{th} , normalized to $M_{\text{max}}^{\text{TOV}}$, linearly correlates with the maximum compactness, defined as $\mathcal{C}_{\text{max}}^{\text{TOV}} \equiv GM_{\text{max}}^{\text{TOV}}/(R_{\text{max}}^{\text{TOV}}c^2)$, where c and G are the speed of light and the gravitational constant, respectively, as well as with other NS equilibrium properties. More recently, also the study of asymmetric BNS mergers has received attention [42, 44–46]. Bauswein *et al.* [42, 44] concluded that PC in asymmetric BNS usually occurs for masses equal or smaller than in the equal mass case, with the possible exception of modest asymmetries and very soft EOSs. The total mass reduction is stronger for

more extreme mass ratios and it has a non-trivial dependence on the NS EOS. Tootle *et al.* [45] suggested instead a quasi-universal relation. In all these works, several fitting formulae to numerical results were provided.

In this *Letter*, we show that K_{\max} , the incompressibility of nuclear, β -equilibrated matter at n_{\max}^{TOV} , determines the behavior of BNS mergers close to PC and, in particular, their dependence on the mass ratio. Our results stem from the largest set of numerical relativity simulations of irrotational, asymmetric binaries with finite temperature, composition dependent microphysical EOSs to date. We demonstrate that the detection of M_{th} at two different mass ratios can provide a direct measurement of K_{\max} in a regime otherwise inaccessible. Additionally, we suggest that its value can yield information about the relevant thermodynamics degrees of freedom close to n_{\max}^{TOV} .

Methods and models.- We simulate 250 irrotational BNS mergers with different gravitational masses $M \equiv M_1 + M_2 \in [2.786M_{\odot}, 3.3M_{\odot}]$ and mass ratios $q \equiv M_1/M_2 \in \{0.6, 0.65, 0.7, 0.75, 0.85, 1\}$. We perform series of simulations at fixed q while changing M to explore the onset of the PC behavior and determine $M_{\text{th}}(q)$. For the definition of $M_{\text{th}}(q)$ and its numerical error, $\delta M_{\text{th}}(q)$, we follow Refs. [42, 43, 47], monitoring the maximum of the rest mass density, n_{\max} , throughout the computational domain. Simulations are performed with the same codes and setup as in Ref. [43]; $q = 1$ data are from Ref. [43], while $q \neq 1$ data are presented here for the first time. See the Supplemental Material [48] for more details, which includes also Refs. [49–91].

To span present uncertainties, we consider six finite-temperature, composition dependent NS EOSs. Four are purely nucleonic and widely used: BL [92, 93], SFHo [94] and HS(DD2) [95, 96, hereafter DD2], and LS220 [97]. Additionally, we consider an EOS including hyperons, HS(BHB ϕ) [98, hereafter BHB], and one including a phase transition to quark matter, DD2qG, also presented in Ref. [43]. In both cases, the nucleonic baseline is DD2. In Figure 1, we present the nuclear incompressibility of neutrinoless, β -equilibrated, cold NS matter, K_{eq} , defined as in Eq. (1) but for $\delta = \delta_{\text{eq}}$, for the six different EOSs above as a function of n_b . For each EOS we highlight $K_{\max} \equiv K(n_{\max}^{\text{TOV}})$. It is striking that the properties in the low density regime ($n_b < 2n_0$) do not necessarily correlate with those at $n_b \sim n_{\max}^{\text{TOV}}$. Moreover, the BL, SFHo and LS220 EOSs, despite being softer than the DD2 EOS, reach larger n_{\max}^{TOV} and provide similar, if not larger, K_{\max} .

Results.- Our simulations robustly indicate that PC occurs as n_{\max} approaches n_{\max}^{TOV} at merger. With the exception of the DD2qG EOS, for which $n_{\max} \sim 0.8 - 1.2n_{\max}^{\text{TOV}}$, for the heaviest non-PC BNS we observe $n_{\max} \sim 0.75 - 0.95n_{\max}^{\text{TOV}}$ at the first remnant bounce, with larger values usually associated to $q \sim 1$. Two opposite effects influence the evolution of n_{\max} with respect

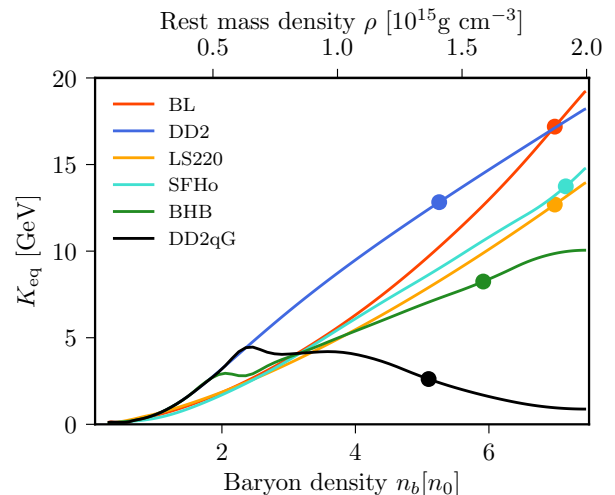


FIG. 1. Nuclear incompressibility K_{eq} of cold, β -equilibrated nuclear matter as a function of baryon density for the EOSs employed in this work. Solid markers correspond to K_{\max} , i.e. K_{eq} at the central density of the heaviest, irrotational NS.

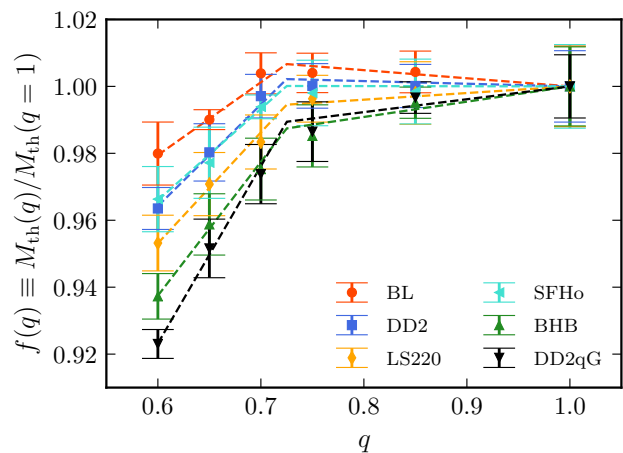


FIG. 2. Threshold PC masses normalized to the $q = 1$ case as a function of q for all the EOS used in this work. Dashed lines correspond to Eq. (2) fit.

to q . On the one hand, for a given M , binaries with smaller q 's have smaller orbital angular momentum and the NS cores are more prone to fuse (and thus to increase n_{\max} toward n_{\max}^{TOV}) due to the smaller rotational support [42, 44]. On the other hand, the nuclear incompressibility usually increases as n_{\max} grows, providing a larger nuclear repulsion that contrasts its further increase. Since PC is observed for $n_{\max} \sim n_{\max}^{\text{TOV}}$, it is understandable that K_{\max} is the incompressibility value relevant for the PC behavior.

To analyse the dependence of PC on K_{\max} , in Figure 2 we first consider $f(q) \equiv M_{\text{th}}(q)/M_{\text{th}}(q = 1)$ for

all EOSs, where (to be conservative) the error bars have been obtained by propagating the errors both on $M_{\text{th}}(q)$ and $M_{\text{th}}(q = 1)$. Values of M_{th} and δM_{th} are reported in the Supplemental Material [48]. We first observe that our results do not have a universal behavior for the different EOSs. Second, we notice that a variation of almost a factor of 1.7 in q has a small effect on $M_{\text{th}}(q)$, with the corresponding variation in $f(q)$ ranging between 3% and 8%, larger for EOSs with a smaller K_{max} . This is broadly compatible to what observed in [42, 44–46] and should be compared with the larger ($\lesssim 20\%$) variation in $M_{\text{max}}^{\text{TOV}}$ or $M_{\text{th}}(q = 1)/M_{\text{max}}^{\text{TOV}}$ reported in Refs. [34, 38, 40–43, 47].

Focusing on the behavior of $f(q)$ for $0.7 \lesssim q \leq 1$ we observe that, depending on the EOS, $f(q)$ can decrease, stay approximately constant or even increase as q decreases [see also 44, 46, 99]. We interpret this as the result of the interplay between the binary orbital angular momentum and the incompressibility of nuclear matter, in light of the merger dynamics. For BNSs with $q \lesssim 1$ and $M \approx M_{\text{th}}$, the central density inside the more massive NS ranges in 0.40–0.49 n_{max} (depending on the EOS) and the merger is driven by the fusion of two comparable NS cores. If K_{eq} increases steeply enough with n_{max} , nuclear repulsion contrasts efficiently gravity-driven compression. The net result is that for EOSs with a relatively large K_{max} (as BL, SFHo and DD2), $M_{\text{th}}(q \lesssim 1)$ can stay rather constant or even increase as q decreases. On the opposite, if K_{eq} does not increase significantly with n_b and K_{max} is relatively low (as for DD2qG and BHB), nuclear repulsion is not enough to counterbalance the lack of rotational support and PC occurs for $M_{\text{th}}(q \lesssim 1) < M_{\text{th}}(q = 1)$.

Moving to $0.6 \lesssim q \lesssim 0.7$, we notice a clear change of behavior: $f(q)$ decreases as q decreases for all EOSs. But, once again, the variation depends sensitively on K_{max} : EOSs characterized by a smaller K_{max} result not only in smaller $f(q)$, but also in larger relative variations with respect to $f(q \approx 0.7)$. We explain this transition in terms of the different merger dynamics. For BNSs at the PC threshold and with $q \lesssim 0.7$, the central density inside the more massive NS increases to 0.5–0.57 $n_{\text{max}}^{\text{TOV}}$, while the secondary NS is more significantly deformed and tidally disrupted during the last orbits. As q decreases, the denser core of the more massive NS is compressed by more massive streams of accreting matter [33, 36, 42, 100, 101]. The nuclear incompressibility still opposes compression, but less efficiently than in the $0.7 \lesssim q \leq 1$ regime. K_{max} still provides a measure of the NS matter resistance to compression in the relevant density interval and different EOSs result in different relative variations.

Our data qualitatively agree with those from independent simulations recently reported in Refs. [41, 45, 46]. However, quantitative differences comparable to the overall variation observed in our results are found. This is possibly due to different definitions of PC threshold, gravity treatment or numerical resolutions. A compari-

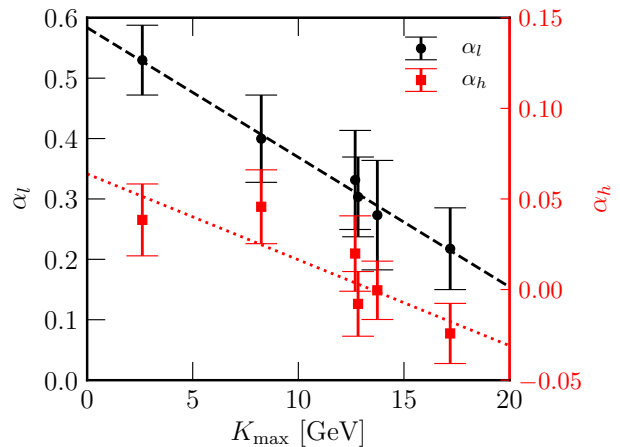


FIG. 3. Slopes of the fitting coefficients $\alpha_{l,h}$ for data in Figure 2 as a function of K_{max} . Both slopes show a trend with K_{max} that we fitted with a linear function (dashed lines).

son with the some of the available fits is reported in the Supplemental Material [48]. Moreover, our extended set of EOS indicates a sub-leading but significant and systematic EOS dependence emerging for asymmetric binaries, in contrast to a quasi-universal behavior [45].

Figure 2 suggests the existence of two different regimes, separated by $0.7 \lesssim \tilde{q} \lesssim 0.75$, which is largely independent from the EOS. In each of the two regimes, $f(q)$ is well described by a linear relation. Thus, for each EOS we fit our data by considering:

$$f(q) = \alpha(q)q + \beta(q) = \begin{cases} \alpha_l q + \beta_l & \text{if } q < \tilde{q}, \\ \alpha_h q + \beta_h & \text{if } q \geq \tilde{q}. \end{cases} \quad (2)$$

We fix $\beta_{l,h}$ in Eq. (2) by imposing the continuity of $f(q)$ at $q = \tilde{q}$ and $f(q = 1) = 1$. Moreover, we assume $\tilde{q} = 0.725$ by closely inspecting Figure 2. Least square fits (dashed lines) are performed on the two parameters $\alpha_{l,h}$, corresponding to the slopes of the two linear regimes. The residuals relative to the errors are always smaller than 0.5 and without clear systematic trends both with respect to the EOS and q .

Our simulations reveal a correlation between $\alpha_{l,h}$ and K_{max} supporting the interpretation that the latter is one of the key properties that control the PC. In Figure 3, we represent $\alpha_{l,h}$ with their uncertainties as a function of K_{max} for each EOS. Given the reduced number of EOSs and the relatively large uncertainties, we fit $\alpha_{l,h}$ with a first order polynomial in K_{max} (dashed lines in Figure 3):

$$\begin{aligned} \alpha_l &= -(22 \pm 1)\text{TeV}^{-1}K_{\text{max}} + (0.58 \pm 0.01), \\ \alpha_h &= -(4.7 \pm 1.0)\text{TeV}^{-1}K_{\text{max}} + (0.064 \pm 0.017). \end{aligned} \quad (3)$$

The slopes of the linear behaviors observed in Figure 2 usually decrease as the incompressibility increases. This

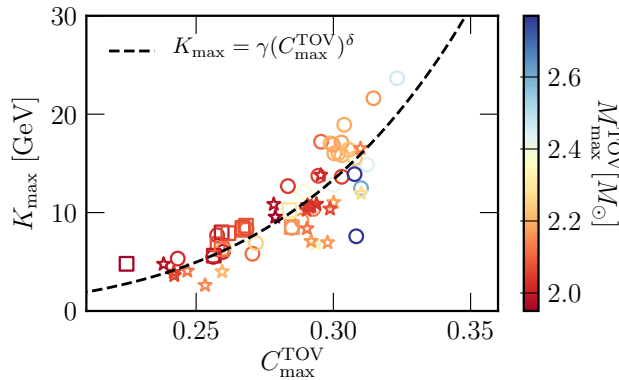


FIG. 4. K_{\max} as a function of the compactness of the heaviest NS for a large sample of EOSs. Circles correspond to nucleonic EOSs, while squares and stars to EOSs containing hyperons or undergoing a phase transition to quarks, respectively.

confirms that EOSs with a large incompressibility provide a possible increase in M_{th} for $\tilde{q} < q \leq 1$ and a less steep decrease for $q < \tilde{q}$.

Discussion.— Our results suggest that the determination of M_{th} at two different q 's, $q_{1,2}$, allows to determine K_{\max} by solving:

$$\frac{M_{\text{th}}(q_1)}{M_{\text{th}}(q_2)} = \frac{\alpha(K_{\max}, q_1)q_1 + \beta(\alpha)}{\alpha(K_{\max}, q_2)q_2 + \beta(\alpha)}, \quad (4)$$

where α and β are defined consistently with Eqs. (2) and (3). To test this, we repeat the previous fits excluding results from the SFHo EOS. The new fitted coefficients, $\alpha'_{l,h}$, are compatible to within uncertainties with $\alpha_{l,h}$ in Eq. (3). We deduce K_{\max} for SFHo using these new fits and the $M_{\text{th}}(q)$ SFHo results at two different q 's. In particular, we randomly sample the intervals $(M_{\text{th}}(q) \pm \delta M_{\text{th}}(q)/2)$ one thousand times to set simulated values for the threshold masses, $\tilde{M}_{\text{th}}(q_{1,2})$, and to compute \tilde{K}_{\max} by solving Eq. (4). We finally extract the average relative discrepancy between the computed and actual values. For example, using $M_{\text{th}}(q = 0.65)$ and $M_{\text{th}}(q = 0.85)$ we recover K_{\max} to within 2% of its actual value. The uncertainty increases when considering $M_{\text{th}}(q = 0.7)$ and $M_{\text{th}}(q = 0.85)$. In this case, K_{\max} is recovered to within 15%. Our method does not necessarily require the knowledge of $M_{\text{th}}(q)$ at two $q \neq 1$. For example, using $M_{\text{th}}(q = 0.7)$ and $M_{\text{th}}(q = 1)$ we recover K_{\max} within 3.5%. The above discrepancies on K_{\max} are compatible with the uncertainties implied by Figure 3.

To further challenge our method, we consider the independent results for $M_{\text{th}}(q)$ from Ref. [45] obtained for irrotational NSs and for the TNTYST EOS [102], an EOS not included in our sample and for which $K_{\max} > 20\text{GeV}$

¹. We consider the $\alpha_{l,h}$ fits, Eq. (3), and we solve Eqs. (4) and (5) using $M_{\text{th}}(q = 0.7)$ and $M_{\text{th}}(q = 0.9)$. Despite possible systematical differences related to the different way to determine M_{th} , we recover the expected value of K_{\max} to within 25% ($\sim 6\text{ GeV}$) of its actual value.

Prompted by these results, we investigate a direct correlation between C_{\max}^{TOV} and K_{\max} and we find that the values of K_{\max} can provide information on the relevant degrees of freedom in ultradense matter. In Figure 4, we present K_{\max} as a function of C_{\max}^{TOV} for a large set of EOSs. In particular, we selected EOSs that stay causal up to n_{\max}^{TOV} and for which $M_{\max}^{\text{TOV}} > 1.97M_{\odot}$. More detailed information can be found in the Supplemental Material [48]. Different symbols refer to different particle contents while colors to M_{\max}^{TOV} . We suggest that large $K_{\max} (\gtrsim 15\text{GeV})$ are more easily associated with purely nucleonic EOSs, while EOSs containing hyperons or showing a phase transition to quarks are characterized by small $K_{\max} (\lesssim 15\text{GeV})$. A tighter threshold at 12GeV can be observed if only two EOSs containing just u and d quarks, out a sample of 34 EOSs containing quarks or hyperons, were removed. Moreover, K_{\max} can be fitted in good approximation with a power law, $K_{\max} = \gamma(C_{\max}^{\text{TOV}})^{\delta}$. Standard least squared methods provide $\gamma = (9.2 \pm 5.4)\text{TeV}$ and $\delta = 5.67 \pm 0.50$. Despite not being trivial, such a relation is not surprising, since both M_{\max}^{TOV} and $R_{\text{NS}}^{\text{TOV}}$ depend on the equilibrium response of the heaviest NS to radial perturbations for $n_b \sim n_{\max}^{\text{TOV}}$, and thus on K_{\max} . Moreover, it provides a possible connection between our findings and previous, different fits for M_{th} expressed in terms of M_{\max}^{TOV} and C_{\max}^{TOV} , both for symmetric and asymmetric mergers [39, 40, 42–44, 46]. For example, we have repeated our analysis in terms of C_{\max}^{TOV} rather than K_{\max} , finding comparable results, as reported in the Supplemental Material [48]. Even if this relation directly connects K_{\max} to C_{\max}^{TOV} , we stress that K_{\max} provides a cleaner and more intuitive physical interpretation of the PC behavior for $q \neq 1$.

This $K_{\max}(C_{\max}^{\text{TOV}})$ relation, combined with the linear relation $M_{\text{th}}(q = 1)/M_{\max}^{\text{TOV}} = aC_{\max}^{\text{TOV}} + b$ first proposed in Ref. [39] but with coefficients from Ref. [43], suggests that M_{\max}^{TOV} can be also related to K_{\max} and $M_{\text{th}}(q = 1)$:

$$M_{\max}^{\text{TOV}} = \frac{M_{\text{th}}(q = 1)}{a(K_{\max}/\gamma)^{1/\delta} + b}. \quad (5)$$

Eqs. (2) and (5) together suggest that K_{\max} can be estimated by the knowledge of only one $M_{\text{th}}(q)$, if M_{\max}^{TOV} is known:

$$\frac{M_{\text{th}}(q)}{M_{\max}^{\text{TOV}}(a(K_{\max}/\gamma)^{1/\delta} + b)} = \alpha(K_{\max}, q)q + \beta(\alpha). \quad (6)$$

¹ We notice, however, that the TNTYST EOS becomes acausal close to n_{\max}^{TOV} .

For example, using the $\alpha'_{l,h}$ fits while employing M_{\max}^{TOV} and $M_{\text{th}}(q = 0.85)$ SFHo results as input data, we recover K_{\max} and C_{\max}^{TOV} to within 40% and 1.6%, respectively. Comparable results were obtained from smaller q 's.

The analogy between the definition of K_{eq} and the square of the speed of sound of NS matter, $c_s^2 = \partial P / \partial \epsilon|_{T=0, \delta_{\text{eq}}}$, where ϵ is the density of internal energy, suggests that the measurement of the PC threshold at different q 's can also provide constraints on the value of c_s^2 close to n_{\max}^{TOV} . Indeed, the α and β coefficients of Eq. (2) also correlate with c_s^2 in a comparable way as with K_{\max} and C_{\max}^{TOV} , as visible in the Supplemental Material [48]. Constraints on c_s can provide further insight into the physics governing the EOS of nuclear matter [see e.g. 103, 104].

The larger detection horizon associated to massive BNS mergers suggests that, as in the case of GW190425 [105], PCs are a viable observational phenomenon associated to a significant fraction of BNSs that will become accessible in the next GW observing runs [106, 107] and with 3rd generation GW detectors [108–110]. While current GW detections allow the precise measurement of the chirp mass and, up to a certain extent, of the total mass, the mass ratio is more uncertain. High enough signal-to-noise ratios and good sky localizations favoring followup EM observations will be key to provide better constraints on q . We estimate the possible impact of the uncertainties on M_{th} and on q on the estimate of K_{\max} by solving again Eq. (4), using the $\alpha'_{l,h}$ fitted coefficients (i.e. considering SFHo as our underlying EOS and removing it from our fitting sample). We randomly sample both M_{th} and q within $M_{\text{th}} \pm \Delta M_{\text{th}}$ and $q \pm \Delta q$, where ΔM_{th} and Δq are the uncertainties in the determination of $M_{\text{th}}(q)$. In the case of $q = 0.85$ and $q = 0.65$, to determine K_{\max} with at least 30% accuracy at 90% confidence level we estimate $\Delta M_{\text{th}} \lesssim 0.025 M_{\odot}$ and $\Delta q \lesssim 0.05$. For $q = 0.85$ and $q = 0.70$, the uncertainties should decrease to $\Delta M_{\text{th}} \lesssim 0.01 M_{\odot}$ and $\Delta q \lesssim 0.025$ to get a similar accuracy. The difference between the two cases proves that, due to the larger slope of $M_{\text{th}}(q)$ at $q \ll 1$, the determination of $M_{\text{th}}(q)$ for very asymmetric systems is more constraining. Such uncertainties are within reach of future observations and detectors [111]. More theoretical PC studies will be needed to reduce systematic uncertainties and include more detailed physics. Nevertheless, our results clearly indicate a new and unique way to access critical information on extreme density nuclear physics using observations of promptly collapsing BNS mergers.

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